

Using a Simple Dilution Model to Estimate Wastewater Contaminant Concentrations Behind Moving Passenger Vessels

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Abstract—An independent Science Advisory Panel (The Panel) was formed to assist the Alaska Department of Environmental Conservation evaluate the effects of wastewater discharges from cruise ships in Alaskan waters. The Panel evaluated the dilution of wastewater discharges from moving cruise ships. The results of that evaluation were used in turn to evaluate possible effects on water quality. This paper describes the dilution evaluation.

The Panel evaluated a number of different studies and concluded that 1) the water that is displaced by a moving ship creates turbulent mixing upon its return astern of the ship; 2) the propellers further enhance the turbulence and mixing; 3) a cruise ship can be represented as a moving cross-sectional area; the larger the cross section and/or the faster the cruise ship moves, the greater the volume of water displaced per unit time leading to increased mixing rates; and 4) the diluted concentrations achieved will be inversely proportional to the rate of discharge. Hence, the mixing will be rapid, substantial and related to the vessel's size, speed and discharge rate. Based on two theoretical studies and six field studies, The Panel concluded that the cross sectional mixing area behind a large cruise ship rapidly expands to about 4 times the cross-sectional area (beam times draft) of the ship. The dilution factor (df) for a discharge from a large moving cruise ship can be calculated as follows:

$$df = 4 \times (\text{width} \times \text{draft} \times \text{speed}) / (\text{discharge rate})$$

Links to The Panel's final report, as well as interim reports and other related matters can be found at:

<http://www.state.ak.us/dec/press/cruise/cruise.htm>

I. INTRODUCTION

An independent Science Advisory Panel for the State of Alaska (hereafter referred to as The Panel) was formed in early 2001 to address discharge issues from large cruise ships (greater than 250 passengers). The Panel participated in a three day cruise aboard a large cruise ship, examined the waste handling procedures on board, and also visited a second cruise ship in port. A sub-group of The Panel reviewed previous studies, consulted with marine architects and effluent discharge modelers, and prepared a preliminary analysis of dispersion in June 2001 [1]. The Panel developed a preliminary formula that described the mixing behind a large moving cruise ship as the product of the below water line cross sectional area multiplied by the vessel's speed divided by the discharge rate. The Panel knew that this was a conservative approach and that various studies discussed below showed that there would actually be greater mixing. The Panel recommended that dye studies be conducted and compared to the formula. In July 2001 The Panel met in Juneau, toured several more cruise ships and conducted observations of currents and turbulence behind moving cruise ships. EPA conducted dye studies behind 4 cruise ships off of Miami in August 2001, which one Panel member was able to observe. The Panel used the information from the dye studies and from its own observations to revise the dilution formula (by a factor of 4) and the final dilution analysis was presented in Section I of The Panel's final report in November 2002 [2].

The dilution analysis was the critical information needed to assess various concerns raised by the complex set of effluent graywater and blackwater monitoring data that had been collected. The data collected included conventional pollutants, toxicants, nutrients and bacteria, as well as overall toxicity of the effluent by conducting whole effluent toxicity tests. Other sections of the final report addressed these issues. Water quality criteria were determined not to be exceeded for ships traveling at or greater than 6 knots. Provided vessels discharge at least one nautical mile from shore or shellfish beds, adequate additional dilution occurs, ensuring the protection of human health.

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II. DISCUSSION

In preparing its preliminary analysis of dispersion [1] The Panel considered the following studies.

The Alaska SeaLife Center (ASLC) provided a report that considered near-field dilution of graywater discharged from a typical cruise ship [3]. The CORMIX1 discharge dilution model was used for the evaluation. The mixing was calculated for the plume at the stern of the ship and disregarded any mixing induced by the propellers. A maximum dilution factor of 2,500 was calculated for a discharge of 200 cubic meters per hour and a vessel speed of 8 knots. Though the CORMIX1 model is an EPA approved model, it is designed for discharges from a stationary outfall in a channel. The Panel determined that the CORMIX1 model does not simulate the dynamics related to the ship's hull, displacement or propulsion system. The Panel believed that the plume that forms would undoubtedly be drawn into the propellers and that the dilution that occurs will be largely influenced by the propeller mixing and the returning displacement water from the ships' passage.

Kim [4] assumed cruise ship wastewater will be diluted into a standard mixing zone that is being considered under the ongoing development of Uniform National Discharge Standards for vessels of the Armed Forces. This zone is derived from the assumption of a mixing zone at any point in time as having a radius of 35 m and a depth of 20 m. This zone is effectively a box 70 m in width and 20 m in depth and an overall length dependent on the ship speed. Kim calculated a dilution factor of 78,000 for a typical cruise ship traveling at 6 knots and discharging wastewater at 200 m³/hour. Kim noted that higher speeds would lead to greater dilution factors. The Panel agreed with Kim that dilution factors would vary with speed, but was unsure about the width and depth of the assumed mixing zone. The waters of Southeast Alaska often exhibit sharp density stratification that may restrict mixing to a shallower depth than 20 m.

Diffusion experiments were conducted in the 1970's at a deep-water dumpsite off the New York coast [5]. The discharge was from a towed barge where wake turbulence and re-combined displacement water caused effluent mixing without the assistance of propellers. These observations found that wake dispersion produced initial dilutions up to a factor of 10,000 for a barge traveling at 6 knots. The studies also suggested that mixing turbulence behind a vessel occurs in a vertical area 2.5 times the beam and 3 times the draft. The dimensions of the observed vertical mixing area were proportionally similar to the assumed mixing zone used by Kim. The Panel believed the barge diffusion experiments could be used as a lower bound for mixing estimates, and that propeller induced mixing behind a cruise ship would cause further dilution.

The Panel reviewed a wastewater dispersion study that involved water column sampling behind a discharging cruise ship near Ketchikan, Alaska that compared effluent data for bacteria, COD, BOD, TSS and Ammonia with

measurements in the wake [6]. The bacteria were found to be the most useful tracer of the ship's discharge. The ship was simultaneously discharging from two tanks that had 9,200 and 7,000,000 fecal coliform organisms per 100 ml, and the samples in the receiving water averaged 7.7 organisms per 100 ml at 2 meters, and less than one organism per 100 ml at 5 and 10 meters. The results supported extreme dispersion of discharged wastewaters. Specifics as to discharge rates and vessel speed were not provided.

The Panel concluded that a simple estimate of the dilution of any substance discharged along the hull assumes a well-mixed effluent over a vertical plane with an area that equals the width of the ship multiplied by the draft of the ship and that by considering the ship's speed and the rate of the effluent discharge, a conservative dilution factor (df) could be calculated as shown in (1.1).

$$df = (width \times draft \times speed) / (discharge \text{ rate}) \quad (1.1)$$

Using this formula, considering the beam and draft of three different large cruise ships, and an average discharge rate of 200 m³/hr, dilution factors varied from 10,500 to 13,200 at 6 knots. At 18 knots they varied from 31,500 to 39,600.

The Panel then evaluated maximum and average concentrations for toxicants detected in an extensive sampling of graywater and treated blackwater from 21 cruise ships in the summer of 2000, used a dilution factor of 12,000 and compared the results to Alaska's acute and chronic marine water quality criteria. The calculated dilution was sufficient to assure that no exceedances of toxicant water quality criteria would result.

The Panel considered the dilution estimates from (1.1) to be minimal estimates until further dilution studies became available. Because (1.1) was based largely on theoretical considerations, The Panel recommended that a dilution study with dye and other tracers should be performed to confirm the basic assumptions of the model. The Panel concluded that the dilution factors in the ASLC report [3] underestimated the amount of mixing and rate of dilution.

In July 2001, The Panel performed a study of opportunity behind two cruise ships as they were departing Juneau [7]. The study design involved tracking drogues placed at different depths on the port and starboard side of the wake shortly after a cruise ship passed. The Panel also had the observing vessel cross the wake to see if a trace of the wake turbulence could be observed on the fathometer. The fathometer proved to be very useful for describing the vertical extent of the wake turbulence and was found more useful than the drogues; the depth of turbulence was easily observed. The Panel quickly improvised a method for determining the width of turbulence and the observations were recorded on videotape. For two of the passes through the wakes, The Panel had insufficient information to calculate the width, which explains the question marks in Table 1. The dimensions of the observed wake turbulence are shown in Table 1. The turbulence observations

supported more than three times the mixing that is derived from (1.1).

Both the depth and cross-sectional area of turbulence observed with the fathometer decreased over time. The wake turbulence of a passing ship would be expected to rise some and spread out laterally, but the cross-sectional area of mixing should increase and not contract. The decrease in depth of turbulence observed with the fathometer is probably a signal of entrained bubbles rising to the surface. Effluent would still be mixed with deeper water after the bubbles had gone. Hence, the decreasing observed cross-sectional area of turbulence in Table 1 should not be construed as a decreased area in which effluent is mixed.

The Panel reviewed a study by the Navy that measured and modeled dilution of a pulped waste paper discharge from the stern of a frigate [8]. Unlike a large cruise ship, the frigate was smaller and had just a single propeller. The Panel determined that the measured and modeled dilutions behind the frigate were about 3 times greater than (1.1).

TABLE 1

Fathometer observations of wake turbulence
Vessel: *Ryndam* Speed: 10 knots

Time after ship passed	Depth	Width	Cross-sectional Area
2 minutes	12 m	?	?
6 minutes	7.5 m	125 m	938 m ²
12 minutes	6 m	155 m	930 m ²

Vessel: *Dawn Princess* Speed: 12 knots

Time after ship passed	Depth	Width	Cross-sectional Area
1.5 minutes	18.3 m	?	?
2.6 minutes	12.2 m	76-79 m	928-964 m ²
6 minutes	6.1 m	103-104 m	628-634 m ²
9 minutes	5.5-6.1 m	124-129 m	682-787 m ²
11.7 minutes	4.6-6.1 m	131 m	603-799 m ²
14.6 minutes	3-4.6 m	126-131 m	378-603 m ²
16.5 minutes	2.4-3 m	125-130 m	300-390 m ²

In August 2001, the EPA conducted dye studies of the discharges from four cruise ships off of Miami and presented the results both as measured dilutions and calculated dilutions [9]. The measured dilution factors varied from 195,322 to 643,810 and the calculated dilution factors varied from 255,499 to 907,547. Table 2 shows the widths, drafts, speeds and discharge rates for the four ships and compares EPA's observations to dilutions calculated from (1.1).

The Panel reviewed the final results and determined that the measured dilutions were 5.3, 0.9, 6.5 and 5.1 times that predicted by (1.1) and the EPA calculated dilutions were 4.7, 4.2, 6.7 and 4.5 times that predicted by (1.1). The *M/S Explorer* measured value that was only 0.9 times (1.1) was further evaluated by The Panel and found to be improbable. The Panel concluded that the dye had not thoroughly mixed in the tank, thereby allowing an initial discharge of dye at a much higher concentration than was intended. Using the remaining measured and calculated dilutions, The Panel determined that the dye studies supported adjusting (1.1) by a factor of 4 and that this

would still be conservative. Hence, the recommended formula to calculate dilution factors for large cruise ships in The Panel's final report is shown in (1.2):

$$df = 4 \times (\text{width} \times \text{draft} \times \text{speed}) / (\text{discharge rate}) \quad (1.2)$$

Table 2

Comparison of dilution calculations from (1.1) with EPA measured and calculated dilutions from dye studies

	Units	<i>M/S Majesty</i>	<i>M/S Explorer</i>
Beam	m	32.6	38.6
Draft	m	7.7	8.8
Speed	m/sec	9.0	9.8
Discharge rate	m ³ /sec	0.031	0.016
Equation (1.1)	df	72,000	214,000
EPA measured	df	386,000	195,000
Difference	Factor	5.3	0.9
EPA calculated	df	342,000	908,000
Difference	Factor	4.7	4.2

	Units	<i>M/S Paradise</i>	<i>M/S Fascination</i>
Beam	m	31.4	31.4
Draft	m	7.8	7.8
Speed	m/sec	7.7	4.7
Discharge rate	m ³ /sec	0.019	0.02
Equation (1.1)	df	99,000	57,000
EPA measured	df	644,000	288,000
Difference	Factor	6.5	5.1
EPA calculated	df	667,000	255,000
Difference	Factor	6.7	4.5

Table 3 is similar to Table 2 but compares EPA's observations to dilutions calculated from (1.2) instead of (1.1). Table 3 illustrates that (1.2) agrees well with EPA's dye studies. EPA's dye studies included observations in which both the discharge rates and the speeds of the vessels varied by a factor of 2 (9 to 19 knots and 56 to 112 cubic meters per hour discharge rate).

Table 3

Comparison of dilution calculations from (1.2) with EPA measured and calculated dilutions from dye studies

	Units	<i>M/S Majesty</i>	<i>M/S Explorer</i>
Beam	m	32.6	38.6
Draft	m	7.7	8.8
Speed	m/sec	9.0	9.8
Discharge rate	m ³ /sec	0.031	0.016
Equation (1.2)	df	289,000	854,000
EPA measured	df	386,000	195,000
Difference	Factor	1.3	0.2
EPA calculated	df	342,000	908,000
Difference	Factor	1.2	1.1

	Units	<i>M/S Paradise</i>	<i>M/S Fascination</i>
Beam	m	31.4	31.4
Draft	m	7.8	7.8
Speed	m/sec	7.7	4.7
Discharge rate	m ³ /sec	0.019	0.02
Equation (1.2)	df	398,000	228,000
EPA measured	df	644,000	288,000
Difference	Factor	1.6	1.3
EPA calculated	df	667,000	255,000
Difference	Factor	1.7	1.1

For small cruise ships The Panel recommends a factor of 3 instead of 4 be applied.

III. CONCLUSIONS

Multiple lines of evidence confirm that discharges of wastewaters from moving cruise ships rapidly achieve very high initial dilution factors. No single dilution factor should be used to characterize the mixing for a ship. A simple formulation for dilution behind a passing cruise ship varies with the width and draft of the vessel, the vessel's speed and the rate of discharge. The equation below may be used to describe the mixing for a large cruise ship.

$$df = 4 \times (width \times draft \times speed) / (discharge \ rate)$$

Smaller cruise vessels and ferryboats will behave similarly, but a factor of 3 should be used instead of the factor of 4.

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